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Multi-Spectral QWIP-LED Devices: A Feasibility Study

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Abstract

The recent advances in infrared sensing technology have made it possible to use infrared sensors to support environmental observations, surveillance, threat detection, tracking, and target identification. For space-based ballistic missile defence (BMD) related applications, the most important detector requirements are: high sensitivity, high uniformity, large format, and multicolor capabilities. Quantum well infrared photodetectors (QWIPs) are a relatively new candidate technology for BMD applications. The current Canadian QWIP technology is based on integration of the QWIP with a light emitting diode (QWIP-LED). As the infrared technology continues to advance, there is a growing demand for multispectral (or multicolor) detectors with better target discrimination and identification. The objects of this study are first to identify the current QWIP multi-spectral implementation techniques and then to adapt them to the new QWIP-LED imaging scheme. The scheme has its unique design constraints associated with the QWIP-LED architecture. Some inherent limitations of the QWIP-LED scheme to achieving simultaneous multispectral registration are also discussed. Several multicolor QWIP-LED implementations are described, including two-lead pixelless QWIP-LED devices with sequential multicolor registration and Multi-lead bicolor QWIP-LED focal plane array with near 100% fill factor.

Résumé

Les progrès récents de la technologie de détection infrarouge ont rendu possible l'utilisation de détecteurs aux fins d'observation environnementale, de surveillance, de détection des menaces, de poursuite et d'identification d'objectifs. Dans le cas des applications de défense contre les missiles basés dans l'espace (DMBE), les principales qualités d'un détecteur sont une grande sensibilité, une grande uniformité, un grand format et des capacités multicouleurs. La technologie des photodétecteurs infrafouge à puits quantique (PIPQ) se prête relativement bien aux applications DMBE. La technologie PIPQ canadienne actuelle repose sur l'intégration des PIPQ et d'une diode électroluminescente (PIPQ-DEL). Les progrès constants de la technologie infrarouge expliquent la demande croissante de détecteurs multispectraux (ou multicouleurs) offrant une meilleure capacité de discrimination et d'identification d'objectifs. La présente étude vise à déterminer les techniques d'implantation multispectrale PIPQ actuelles, puis à les adapter à la nouvelle technique d'imagerie PIPQ-DEL. La seule limite de cette technique tient à l'architecture PIPQ-DEL elle-même. Il y est également question de certaines limites de cette technique pour ce qui est de l'enregistrement multispectral simultané. On y décrit plusieurs implantations PIPQ-DEL multicouleurs, dont deux dispositifs PIPQ-DEL sans pixels à deux fils de sortie et enregistrement multicouleurs séquentiel et une matrice focale PIPQ-DEL bicouleurs à plusieurs fils de sortie et facteur de remplissage de 100 pour cent.

Executive Summary

As the infrared technology continues to advance, there is a growing demand for multispectral (or multicolor) detectors with better target discrimination and identification. The objects of this study are first to identify the current multi-spectral implementation techniques for a conventional quantum well infrared photodetector (QWIP) and then to adapt them to a new imaging scheme which integrates the QWIP with a light emitting diode (LED).

Being based on thin multilayers grown by epitaxial techniques, the design of QWIPs is very flexible, and enables various implementations of multicolor detectors. The approaches can be divided into three basic categories: (1) voltage-switched, (2) voltage tuned, and (3) multiple leads. The first method relies on the highly nonlinear and exponential nature of the device dark current-voltage characteristics. The second approach offers continuously tunable response, which can be accomplished by utilizing, for instance, special shapes of quantum wells. The two categories are a two-lead approach and, thus, are simple in fabrication. But the drawback is the difficulty to achieve a negligible electrical crosstalk between colors. Also, both the voltage-switched and the voltage-tuned approaches can only offer sequential multicolor registration. With only two leads available for electrical contacts it would not be possible to differentiate photocarriers generated by incident lights of different wavebands, rendering the two-lead approach a less desirable scheme for ballistic missile defence (BMD) applications.

Two viable configurations for two-lead bicolor QWIP-LED devices were identified and explored. A V-groove coupler or a two-dimensional (2-D) grating can be used to couple the incident infrared light to the quantum wells. Lamellar V-groove couplers are wavelength insensitive and, thus, are suitable for multicolor coupling. On the other hand, the 2-D grating is wavelength specific and the design to cover multiwavebands are much more challenging and, thus, may not be optimized for all wavelengths.

The multi-lead approach is a direct one which involves contacting each intermediate conducting layer separating single-color QWIPs grown in a multi-stack. The result is a separately readable and addressable multicolor QWIP with multiple electrical leads. The advantage of this approach is its simplicity in design and its negligible crosstalk between colors. The drawback is the difficulty in fabrication and, in the case of the conventional QWIP approach, the loss of the fill factor as part of each detector pixel active region is removed to make room for lead contacts. For three-lead bicolor QWIP-LED devices six different QWIP-LED architectural combinations were examined.

An inherent limitation of QWIP-LED architecture is that for multicolor devices the photocarriers generated in separate QWIPs are converted to near-infrared (NIR) lights by their respective LEDs. There is no simple way to differentiate the source of these NIR

lights. One way to separate or differentiate them is by spatial separation. This could be accomplished by an external checkerboard filter or "built-in" checkerboard pixellation of the QWIP-LED device. The external checkerboard approach is simple in both design and fabrication. The drawback is that the device's fill factor is significantly reduced. Thus, compared with the conventional QWIP approach the checkerboard multicolor QWIP-LED scheme may be less appealing. However, the fill factor problem can be overcome by a built-in checkerboard technique. The method involves pixellation of the LED and an intermediate conductive layer. It allows the single-color QWIP fill factor to be kept at nearly 100% while avoiding degradation in the LED performance. Simultaneous bicolor registration is also possible using this approach. However, due to fabrication complexity the technique is very much limited to bicolor devices.

Waveband beam splitter and Brewster's angle beam splitter are two other techniques that could be used to achieve simultaneous multicolor detection. They are simple and do not require modifying the existing QWIP-LED designs. Compared to the multi-stack approach they may not be as compact and elegant. But given that the defect density increases with the number of color stacks and that the fabrication complexity may become increasingly unmanageable for three or more colors, the beam splitter techniques may turn out to be a more viable or the preferred alternative.

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Sommaire

Alors que la technologie de l'infrarouge poursuit ses progrès, la demande visant des détecteurs multispectraux (ou multicouleurs) présentant de meilleures caractéristiques de discrimination et d'identification continue de croître. La présente étude cherche à identifier les techniques de mise en œuvre de la technologie multispectre dans un photodétecteur infrarouge à puits quantique (QWIP) classique et ensuite à les adapter à une nouvelle méthode d'imagerie intégrant le dispositif QWIP à une diode électroluminescente (DEL).

Fondée sur les techniques épitaxiales de croissance de minces couches multiples, la conception des dispositifs QWIP est un processus très souple qui permet la réalisation de diverses configurations de détecteurs multicouleurs. Ces configurations se classent en trois grandes catégories : à commutation par tension, à accord commandé par tension et à fils multiples. La première configuration est basée sur la nature fortement non linéaire et exponentielle des caractéristiques d'intensité et de tension d'obscurité du dispositif. La deuxième permet d'obtenir une réponse pouvant être accordée en continu, ce qui peut être obtenu, par exemple, en faisant appel à des formes de puits quantique particulières. Ces deux configurations comportent deux fils, ce qui en simplifie la fabrication. La difficulté d'obtenir un degré négligeable de diaphotie électrique entre couleurs représente toutefois un inconvénient de cette configuration. En outre, les configurations à commutation par tension et à accord commandé par tension ne peuvent offrir que l'alignement multicouleur séquentiel. Comme il n'y a que deux fils disponibles pour réaliser les contacts électriques, il est impossible de différencier des photoporteuses générées par des lumières incidentes ayant des bandes de fréquence différentes, et les configurations à deux fils ne constituent donc pas des solutions souhaitables pour les applications de défense contre les missiles balistiques.

Deux configurations viables de dispositifs QWIP-DEL bifilaires à deux couleurs ont été identifiées et étudiées. Un coupleur à rainure en V ou un grillage bidimensionnel (2D) peuvent être utilisés pour coupler la lumière infrarouge incidente avec les puits quantiques. Les coupleurs lamellaires à rainure en V sont insensibles à la longueur d'onde et ils se prêtent bien au couplage multicouleur. Par ailleurs, le grillage 2D est spécifique à la longueur d'onde et une conception visant à traiter des gammes d'ondes multiples représente un défi beaucoup plus grand; c'est pourquoi les réalisations faisant appel à cette technique peuvent ne pas être optimisées pour toutes les longueurs d'ondes.

La configuration multifilaire fait appel à une démarche directe qui consiste à insérer des contacts pour chacune des couches conductrices intermédiaires séparant les QWIP monochromes qui ont été formés dans une pile multicouche. On obtient ainsi un dispositif QWIP multicouleur à plusieurs fils dont chacun des éléments peut être lu et adressé individuellement. La simplicité de conception et la diaphotie négligeable entre

couleurs sont les avantages de cette configuration. Ses inconvénients sont sa difficulté de fabrication et, dans le cas de la configuration classique des dispositifs QWIP, la perte du taux de remplissage car une partie de chaque région active de pixel de détecteur est éliminée pour faire place aux contacts des fils de connexion. Six combinaisons architecturales différentes QWIP-DEL de dispositifs bicolores à trois fils ont été étudiées.

L'architecture QWIP-DEL a pour limite inhérente le fait que, dans le cas des dispositifs multicouleurs, les photoporteuses générées dans des QWIP séparés sont converties en lumière dans l'infrarouge proche par leurs DEL respectives. Il n'existe aucun moyen simple de distinguer la source de ces lumières dans l'infrarouge proche. Une technique de séparation ou de différentiation fait appel à la séparation spatiale. Cette dernière peut être réalisée au moyen d'un filtre en damier externe ou en réalisant la pixélisation en damier intégrée du dispositif QWIP-DEL. La méthode faisant appel au filtre en damier externe est simple du point de vue de la conception et de la réalisation. Toutefois, son inconvénient est la diminution importante du facteur de remplissage. Cela réduit l'intérêt du dispositif QWIP multicouleur à filtre en damier externe comparativement au dispositif QWIP classique. On peut toutefois résoudre le problème de baisse du facteur de remplissage en intégrant le filtre en damier. Cette méthode consiste à pixéliser la DEL et à utiliser une couche conductrice intermédiaire. Il est ainsi possible de maintenir le facteur de remplissage à près de 100 % tout en évitant la baisse de performance de la DEL. L'alignement simultané sur deux couleurs est aussi possible avec cette méthode. Par contre, en raison de leur complexité de fabrication, ces dispositifs sont pratiquement limités à deux couleurs.

L'utilisation de séparateurs de faisceau par gammes d'ondes et de séparateurs de faisceau par inclinaison de Brewster sont deux autres techniques qui pourraient être utilisées pour effectuer la détection multicouleur simultanée. Elles sont simples et n'exigent pas la modification des configurations QWIP-DEL existantes. Les applications de ces techniques peuvent être de plus grande taille et moins « élégantes » que les configurations empilées. Cependant, étant donné que la densité des défauts augmente avec le nombre de piles de couleurs et que la complexité de la fabrication peut être de plus en plus difficile à gérer dans le cas de trois couleurs ou plus, les techniques à séparateurs de faisceau pourraient s'avérer plus viables ou même constituer la solution préférée.

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1. Introduction

Current ballistic missile defence (BMD) systems use cooled IR detector material systems such as indium antimonide (InSb), platinum silicide (PtSi), mercury cadmium telluride (MCT), and arsenic doped silicon (Si:As) for missile tracking, discriminating and homing. Quantum well infrared photodetectors (QWIPs) are a relatively new technology to IR sensor applications. There is no BMD system that uses QWIPs at present time. Both MCT detectors and QWIPs offer high sensitivity with wavelength flexibility in mid-wavelength infrared (MWIR), long wavelength IR (LWIR), and very long wavelength IR (VLWIR) regions, as well as multicolor capabilities. They are considered the two most promising near-term IR technologies to meet the BMD requirements.

QWIPs have been developed very rapidly over the past ten years for LWIR applications. The advantages of QWIPs compared to MCT detectors include the mature GaAs growth and processing technologies, which lead to high uniformity, excellent reproducibility, and thus large-area, low-cost staring arrays. The advantage of the MCT material is its small natural semiconductor band gaps which fall into the IR region. By properly controlling the composition x in $Hg_{1-x}Cd_xTe$, one can vary the band gap of MCT from 0 eV to 1.45 eV which, in theory, could cover IR ranges from 1 to longer than 50 μm. However, MCT is also a very challenging material for IR detection. HgTe is a semi-metal, in which the Hg-Te bond is very weak and is further destabilized by being alloyed with CdTe. The high mercury vapor pressure and the Hg-Cd-Te phase diagram shape result in serious difficulties in repeatable and uniform growth. The soft but brittle nature of the MCT material and substrates makes the device processing difficult. The quality of the material and available large area substrate affects large-format MCT focal plane arrays (FPAs). QWIPs, on the other hand, use III-V materials which have much wider natural semiconductor band gaps (1.43 eV for GaAs) than MCT. The advantages of a wider band gap material are that it gives superior bond strengths and chemical stability, well-behaved dopants, thermal stability, and intrinsic radiation hardness. The major difference a QWIP has from other IR photodetectors is that it uses intersubband transition in the quantum wells (QWs) instead of valence-band-to-conduction-band transition. A QWIP has a relatively low quantum efficiency (QE) because of the nature of intersubband transition. As a result, it is very hard for a QWIP to achieve the high QE of MCT detectors. It is clear that LWIR QWIP cannot compete with MCT photodiodes as the single device [1] especially at higher temperature operation (>70 K) due to fundamental limitations associated with intersubband transitions. However, the advantage of MCT is less distinct in temperature range below 50 K due to problems involved in MCT material, such as p-type doping, Shockley-Read recombination, trap-assisted tunneling, surface and interface instabilities. Even though the QWIP is a photoconductor, several of its properties such as high impedance, fast response time, long integration time, and low power consumption well satisfy the requirements for fabrication of large FPAs.

Due to the high material quality at low temperature, QWIP has potential advantages over MCT for VLWIR FPA applications in terms of the array size, uniformity, yield and cost of the systems [1].

For spaceborne surveillance systems, low background IR seeker/tracker systems, reliable and affordable sensors with long life are needed which can function effectively at temperatures higher than the 20-30 K currently required for bulk photon detectors. Improvement in surveillance sensors and interceptor seekers require large area, highly uniform and multicolor (or multispectral) IR focal plane arrays involving LWIR and VLWIR regions. As the IR technology continues to advance, there is also a growing demand for multispectral detectors for advanced IR systems with better target discrimination and identification. So far, the multiple waveband measurements have been achieved using separate FPAs with a diachronic filter, a mechanical filter wheel, or a dithering filter, a mechanical filter wheel, or a dithering system with a striped filter [1]. These approaches are expensive in terms of size, complexity, and cooling requirement. At present considerable efforts are directed to fabricate a single FPA with multicolor capability to eliminate the spatial alignment and temporal registration problems associated with separate arrays, to simplify optical design, and to reduce size, weight, and power consumption.

Both MCT detectors and QWIPs offer the multicolor capability in the MWIR and LWIR range. Considerable progress has been recently demonstrated by research groups at Hughes Research Laboratory [2] and Lockheed Martin [3] in multispectral MCT detectors employing MBE and MOCVD for the growth of variety of devices. Devices for the sequential and simultaneous detection of two closely spaced subbands in the mid-wavelength infrared (MWIR), the sequential detection of MWIR and LWIR radiation, as well as the sequential detection of two subbands in the LWIR have been demonstrated [2]. One of such two-color MCT detector is the bias-selectable back-to-back photodiode. This device is formed by sequentially growing n-p-p-n four-layer or n-p-n three-layer double heterojunction structures with two MCT photodiodes [2]. In one mode, the MW junction is reverse-biased, producing a signal for the MWIR; and the LW junction is forward-biased polarity, producing no signal. Reversing the bias polarity activates the LW junction but not the MW junction. The successful demonstration of the prototype 128×128 array operated as back-to-back diodes for the simultaneous detection of two closely spaced subbands in the MWIR spectrum has been given by Rajavel *et al.* [2]. The device structures were delineated as mesa isolated structures and contacts were made to the top n-type layer and the intermediate p-type layer. Fill factors as high as 80% were achieved by using a single mesa structure to accommodate the two indium bump contacts required for each unit cell, and quantum efficiency greater than 70% in each band was obtained. Imagery was acquired at temperature as high as 180 K without any visible degradation in image quality.

For QWIPs, several approaches [4-8] to achieving multicolor QWIP detection have been proposed including two stack, two color MW/LW QWIPs at the single device level with either three terminal simultaneous registration [4,5] or voltage tunable between MWIR and LWIR [6]. Also asymmetrically coupled quantum well structures are used to achieve voltage tunable three-color detection within one atmospheric widow [7]. Two-color 256×256 FPAs, in near-infrared (NIR)/LWIR and MWIR/LWIR bands, have been fabricated by Lockheed Martin [8] in a simple way — by stacking quantum well layers with the desired spectral responses. The dual band detector array structure was designed to interface with the existing 512×512 LWIR design readout integrated circuit (ROIC) which is not optimized for MWIR or dual band operation. Also currently, Jet Propulsion Laboratory (JPL) is developing a 640×486 LWIR and VLWIR dual-band QWIP FPA [9].

The objects of this study is firstly to identify the current multi-spectral implementation techniques and then to adapt them to a novel QWIP imaging scheme proposed by H.C. Liu [10] of Institute for Microstructural Sciences, National Research Council of Canada. The new imaging scheme involves integrating a standard QWIP with a light emitting diode (LED). The principle of its operation is described in detail in Ref. [11]. Basically, the QWIP detects MWIR/LWIR radiation which is converted to photocarriers. The carriers are then injected into the LED active layer for their up-conversion to NIR light. The LED output is in turn captured by a standard CCD imaging chip. This QWIP-LED imaging technique offers the potential of fabricating large area (up to 4×4 cm^2) pixelless imaging sensors with elimination of hybridization integration with a silicon ROIC. The scheme, however, has unique constraints associated with the QWIP-LED architecture which needs to be taken into account when designing a multicolor QWIP-LED/CCD integrated sensor. The study identifies these constraints and suggests implementation techniques. Also, some inherent limitations of the QWIP-LED scheme to achieving simultaneous multispectral registration are discussed. The study then concludes with recommendations and future directions.

2. Multi-Spectral QWIP Implementations

Being based on thin multilayers grown by epitaxial techniques, the design of QWIPs is very flexible. This enables various implementations of multicolor (or multi-spectral) detectors. The approaches can be divided into three basic categories: (1) voltage switched, (2) voltage tuned, and (3) multiple leads. The first two categories are a two-lead approach. The three cases are schematically shown in

Figure 1. In general, a multi-color detector is a device having its spectral response varied with parameters like voltages or any other parameters such as pressure, magnetic field, filter position, and so on.

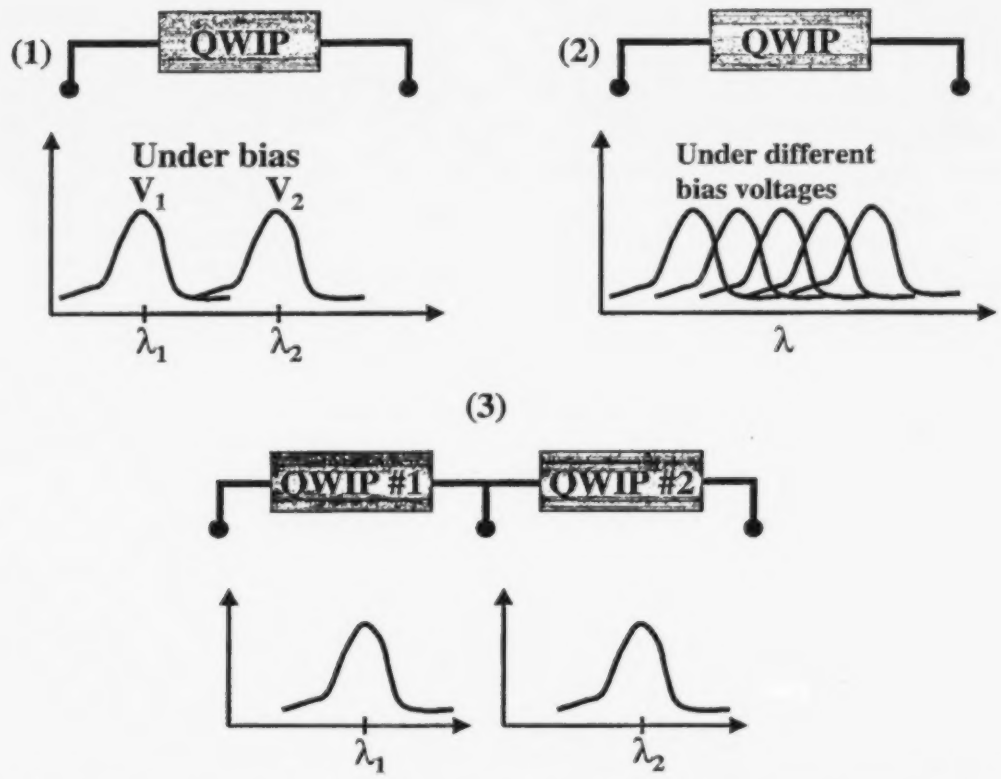

Figure 1 **Three different multicolor QWIP approaches: (1) The QWIP has a response peaked at λ_1 at voltage V_1 and at λ_2 at voltage V_2; (2) The QWIP has a response that is continuously tuned by voltage; and (3) shows two QWIPs with different response wavelengths grown in a multi-stack. Intermediate leads are provided so that each QWIP functions independently.**

2.1 Two-lead Approaches

2.1.1 Voltage-Switched Approach

The first two-lead approach (Figure 1.1) is to have a QWIP with a switchable response; e.g., for an applied voltage V_1 the response is at λ_1 and for V_2 at λ_2. One such example is realized by stacking the usual single-color QWIPs separated by thin conducting layers [12,13]. The method relies on the highly nonlinear and exponential nature of the device dark current-voltage (I-V) characteristics. This implies that an applied voltage across the entire multi-stack would be distributed among the single-color QWIPs according to their values of dc resistances. Thus, when the applied voltage is increased from zero, most of the voltage will be dropped across the one-color QWIP with the highest resistance. As the voltage is further increased, an increasing fraction of the voltage will be dropped across the next highest resistance single-color QWIP, and so on.

Since the detector responsivity of a single-color QWIP gradually turns on with applied voltage, we therefore can achieve a multicolor QWIP with spectral response peaks that turn on sequentially with applied voltage.

The band-edge profiles of a three-color version are schematically shown in Figure 2.1. The use of a photoconductive detector usually involves applying a constant dc bias across detector in series with a load resistor R_s. The equivalent circuit of this three-color detector involves a network of photocurrent sources (i_{p1}, i_{p2}, *and* i_{p3}) and dynamic device resistances (r_1, r_2, *and* r_3), as shown in Figure 2.2. Under small signal condition, the measured photoresponse current is

$$I_{photo} = \frac{i_{p1}r_1 + i_{p2}r_2 + i_{p3}r_3}{R_s + r_1 + r_2 + r_3}.$$

The non-linear nature of the dynamic resistances as a function of the voltage leads to non-linear weighting factors for i_{p1}, i_{p2}, *and* i_{p3} contributions to I_{photo}. The advantage of this approach is that it is simple in fabrication (as it requires only two terminals) and suited for implementing a QWIP with many colors. The drawback is the difficulty to achieve a negligible electrical crosstalk between colors. A similar multicolor QWIP based on high and low field domains has been demonstrated by Gravé *et al.* [14].

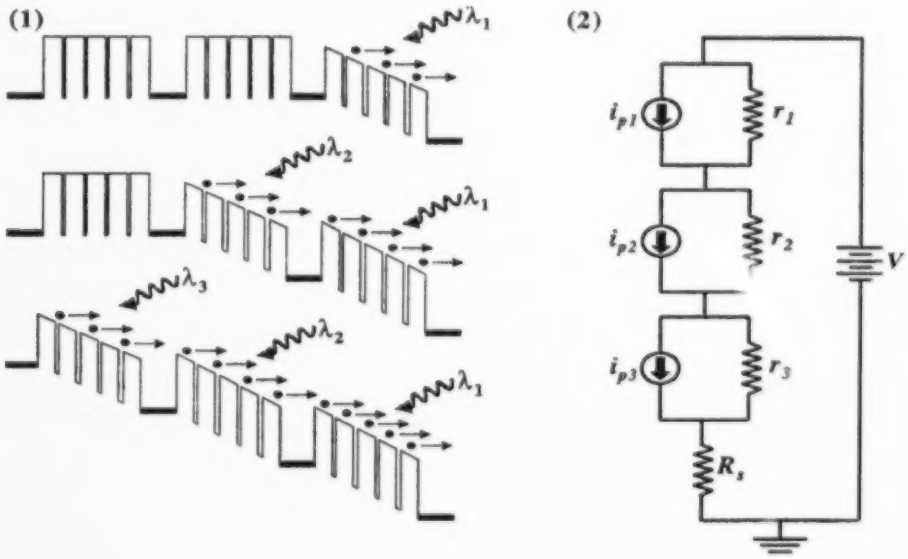

Figure 2 **(1) Bandedge profile of a three-color detector at different bias voltages. The top part is for a small voltage where only the highest resistance one-color QWIP (at λ_1) is turned on; the middle part is appropriate for the situation where two of the three one-color QWIPs (at λ_1 and λ_2) contribute to the photocurrent; and in the lower part the applied voltage is high enough so that all three one-color QWIPs (at λ_1, λ_2 and λ_3) are turned on. (2) Model equivalent circuit of a three-color detector biased through a series load resistor.**

2.1.2 Voltage-Tuned Approach

The second approach (Figure 1.2) is a QWIP with its response continuously tuned in a range of wavelengths. Some examples of this approach utilize special shapes of quantum wells so that the response spectrum shifts as a function of applied bias voltage. This provides a continuous tuning of the spectrum by moving the intersubband resonance position. A range from 8.5 to 13.5 μm has been achieved using stepped wells (Martinet *et al.* [15]). The large continuous tuning capability is the distinct feature of this approach. The difficulty is to ensure a good QWIP performance for all voltages. To accomplish this, the transition final state (usually the first excited state) must be close to (i.e. in resonance with) the top of the barrier [16], providing a large intersubband transition strength and, at the same time, a easy escape for the excited carriers. These two conditions are difficult to fulfill for all voltages. Another factor, which may degrade the QWIP performance, is the use of relative wide wells as in the case of a stepped well. This may lead to an enhanced trapping probability and hence a shorter carrier lifetime.

2.1.3 Implementations of Two-lead Bicolor QWIP-LED Devices

There are two viable configurations for two-terminal bicolor QWIP-LED devices: (1) nQWIP-LED-pQWIP and (2) nQWIP-nQWIP-LED. These are depicted in Figures 3 and 4. Due to a polarization selection rule [17] which permits only the light polarized in growth direction to be absorbed, a diffraction grating or a lamellar V-groove coupler is required for n-QWIP to couple incoming LWIR light to the QWs. Diffraction gratings, however, are known to be wavelength specific, which means that the design of a grating structure suitable for two or more wavebands is difficult. Lamellar V-grooves, on the other hand, are not wavelength sensitive and , thus, are more suitable for multi-waveband coupling. Since p-type QWIPs do not require a grating or a V-groove coupler (see discussion in Sec. 2.2.2), the nQWIP-LED-pQWIP structure needs optical coupling only for the nQWIP, allowing the option of choosing either a diffraction grating or a lamellar V-groove structure for coupling FIR light to the nQWIP; see Figure 3.

For pixelless focal plane QWIP-LED devices, the voltage-switched approach discussed above (Sec. 2.1.1) may not be feasible since thin conducting layers are sandwiched between QWIPs of different wavelength responses. This layers will allow photocarriers to spread laterally and smear the IR image. In order for this multicolor scheme to work, some form of pixellation is required in order to localize the photocarriers to within a pixel. However, the voltage-switched method can also be implemented without the intermediate conducting layers [14] with slightly different I-V characteristics. In this case the QWIP-LED sensors can be implemented in the pixelless form. The voltage-tuned approach can also be implemented easily in a pixelless QWIP-

LED focal plane since no thin conducting layers are sandwiched between the QWIP layers or between the QWIP-LED layers.

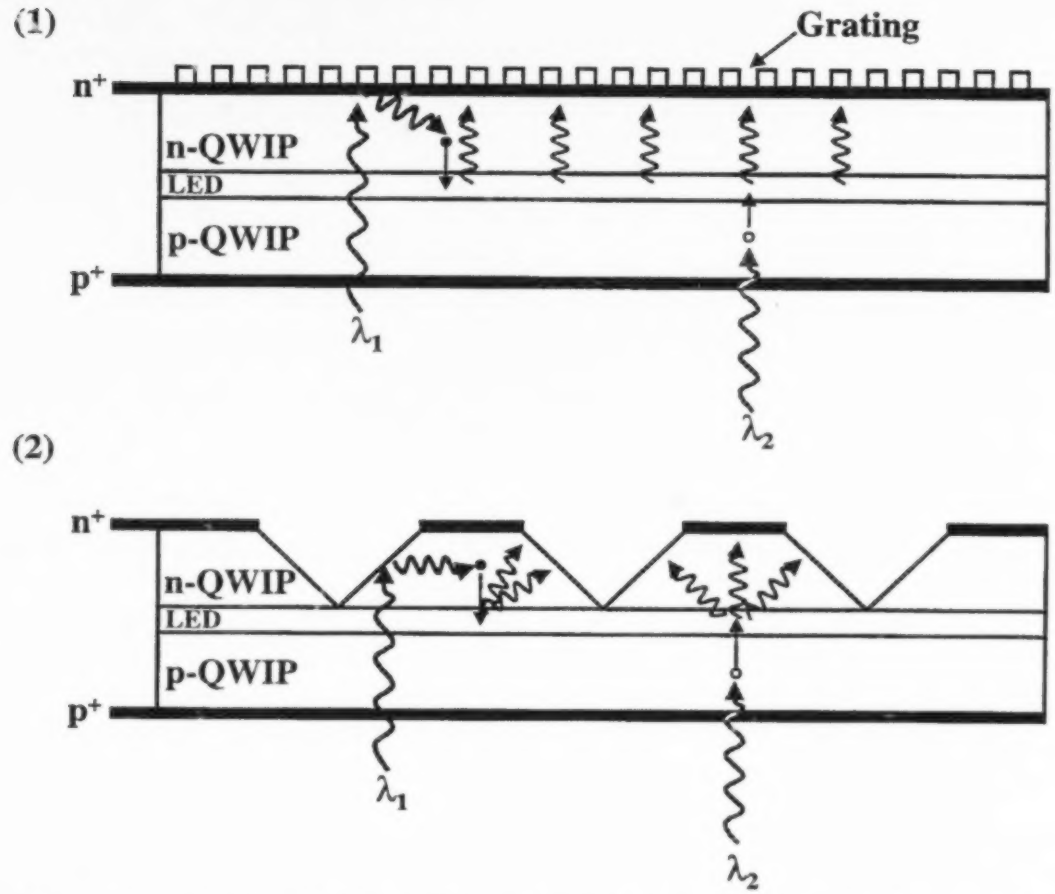

Figure 3 **Implementation of a two-lead bicolor QWIP-LED focal plane with either (1) a 2-D grating or (2) a V-groove coupler.**

Both the voltage-switched and the voltage-tuned approaches, however, can only offer sequential multicolor registration. In order to achieve simultaneous multicolor detection some "middle ground" bias voltage must be applied so that multi-waveband IR lights can be absorbed by the QWs simultaneously. But with only two leads available for electrical contacts it would not be possible to differentiate photocarriers generated by incident lights of different wavebands. Thus, there would be no means by which simultaneous multicolor registration can be realized via the two-lead scheme. Therefore, the two-lead approach to multicolor detection can only provides us with sequential registration of images of different wavebands. Furthermore, even with the sequential multicolor registration, the unavoidable electrical crosstalk between different colors (as

discussed above) might render the two-lead approach a much less desirable scheme for BMD applications.

The use of the V-groove coupler may be preferred for the two-lead QWIP-LED structure #2, since both QWIPs are n-type and require an optical coupler to couple the incident IR to their respective QWs. As already mentioned, lamellar V-groove couplers are not wavelength sensitive; thus, they can be used to couple IR light of any wavelength. The use of a 2-D grating is more limited since the design of a 2-D grating to cover multi-wavebands are much more challenging and may not be optimized for all wavelengths simultaneously. Also, it was found [18] that wet-etching V-grooves through the LED layer appeared to damage the LED, reducing its electroluminescent (EL) intensity by up to an order of magnitude [18]. The cause for this reduction in EL emissions is not known but may be attributed to "unpassivated" facets being exposed by wet-etch leading to nonradiative recombination current paths along these facets. [We are currently exploring LED facet passivation techniques for minimizing nonradiative recombination losses.] Therefore in order to avoid etching of the LED layer, it is necessary to grow the LED layer first and then the QWIPs on the top; see Figure 4. The drawbacks of the V-groove coupler are the reduction in the fill factor and the one-dimensional nature of V-groove structure which is capable of coupling only one component of the electrical field vector.

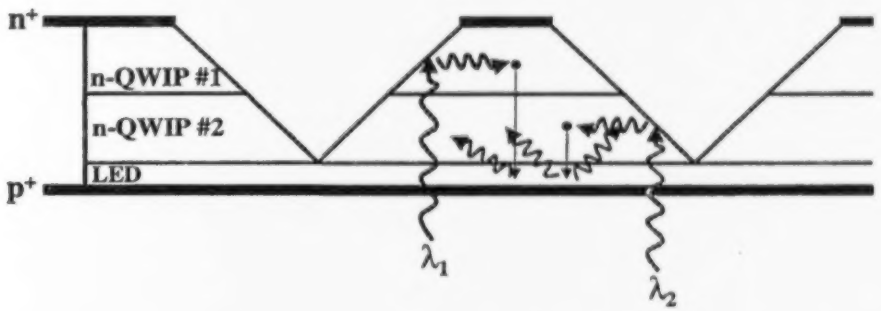

Figure 4 **Implementation of a two-lead bicolor QWIP-LED focal plane using the two-lead architecture #2.**

2.2 Multi-lead Approaches

Approach (3) is a direct one which involves contacting each intermediate conducting layer separating single-color QWIPs grown in a multi-stack; see Figure 1.3 & Figure 5. This results in a separately readable and addressable multicolor QWIP with multiple electrical leads. A two-color version has been demonstrated by Köck *et al.* [6].

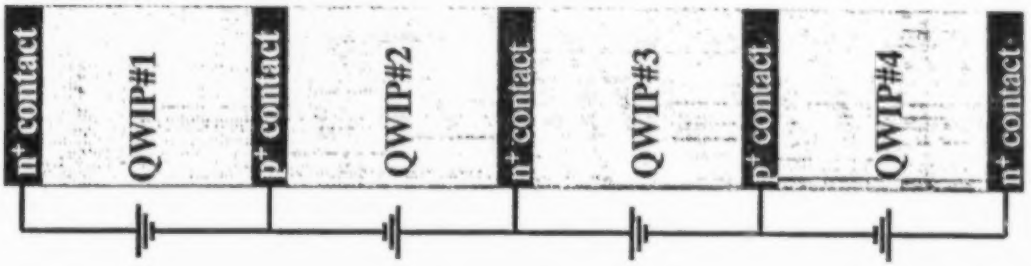

Figure 5 **Multi-stacks of QWIPs which are independently addressable by multiple contact leads.**

2.2.1 Conventional QWIP-MUX devices

In conventional QWIP array detectors, the photodetector is bonded by an array of conducting bumps of indium metal onto a multiplexer (MUX) array; see Figure 6. The MUX is an electronic circuit-on-a-chip which divides up the active surface into pixels. Image detection is possible by separately counting the number of electrons (or holes) generated in each square of the detector.

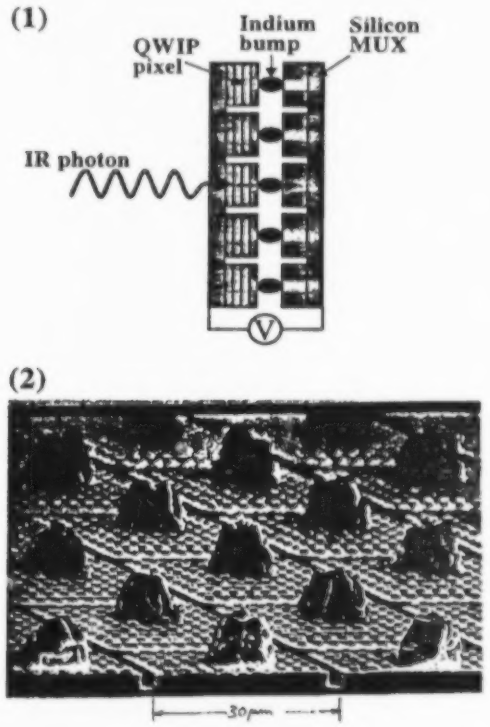

Figure 6 **(1) Schematic of a QWIP-MUX array (side view); (2) An SEM picture showing QWIP array with pixels in the size of 30mm × 30mm, and Indium bumps on them [19].**

2.2.2 Implementations of Multi-lead Bicolor QWIP-LED Devices

For three-terminal bicolor QWIP-LED devices there are at least six different combinations of QWIP-LED structures that could be explored:
(1) $\mathbf{n^+}$-nQWIP-LED-$\mathbf{p^+}$-LED-nQWIP-$\mathbf{n^+}$,
(2) $\mathbf{p^+}$-LED-nQWIP-$\mathbf{n^+}$-nQWIP-LED-$\mathbf{p^+}$,
(3) $\mathbf{p^+}$-pQWIP-LED-$\mathbf{n^+}$-nQWIP-LED-$\mathbf{p^+}$,
(4) $\mathbf{n^+}$-nQWIP-LED-$\mathbf{p^+}$-pQWIP-LED-$\mathbf{n^+}$,
(5) $\mathbf{n^+}$-LED-pQWIP-$\mathbf{p^+}$-pQWIP-LED-$\mathbf{n^+}$,
(6) $\mathbf{p^+}$-pQWIP-LED-$\mathbf{n^+}$-LED-pQWIP-$\mathbf{p^+}$.

The structure #1 has the limitation that the LED layers are sandwiched in between the two n-type QWIPs. Since n-QWIPs are subject to the polarization selection rule, optical couplers are required for both QWIPs in this QWIP-LED architecture. At first, the V-grooves appear to be the optical coupler of choice, but further considerations showed that this bicolor QWIP-LED architecture (see Figure 7) requires V-grooves to be etched through the LED layers. As mentioned earlier, this causes damage to the LEDs and significantly reduces the EL emission. On the other hand, wideband or multiband 2-D gratings can be used but, as discussed earlier, are more difficult to design and usually not optimized for all wavebands of interest.

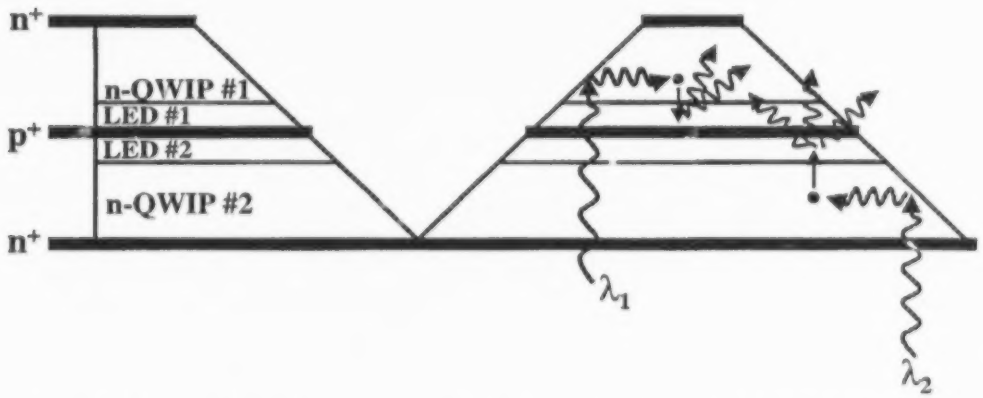

Figure 7 **Schematic showing the structure #1 of a two color, three-lead QWIP-LED device.**

The QWIP-LED architecture #2 suffers similar limitations as #1. Both QWIPs are n-type and thus require optical couplers to promote IR absorption; see Figure 8. Also, if a V-groove coupler is used it is not possible to avoid cutting through at least one of the LED layers. The only remaining choice is therefore a 2-D grating.

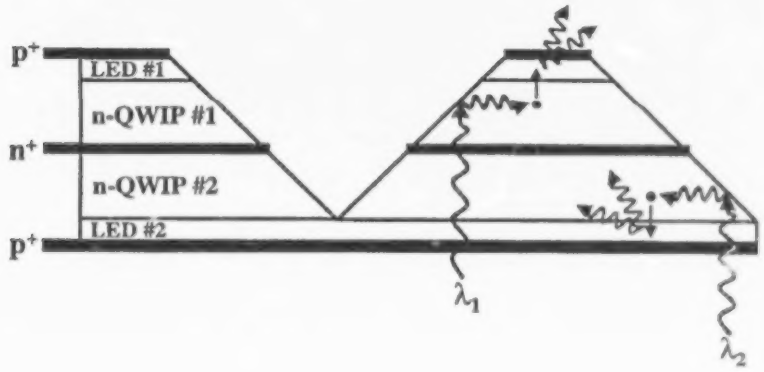

Figure 8 Schematic showing the structure #2 of a two color, three-lead QWIP-LED device.

The third and fourth QWIP-LED architectures use both n-type and p-type QWIPs for bicolor detection. The third structure, however, offers less flexibility than the fourth one because its layer structure requires that V-grooves, if chosen as the IR coupler for the n-QWIP, be etched through the LED layer; see Figure 9. Although one could adopt a 2-D grating instead of V-grooves for this architecture. The p-QWIP is not subject to the polarization selection rule as the n-QWIP and, thus, does not need an optical coupler. The strong mixing between the light and heavy holes in the valence band at $k \neq 0$ [20,21] allows normal incidence absorption. However, most of the efforts to date have been concentrated on the study of n-type QWIPs due to the fact that the performance of p-QWIPs is inferior to that of n-QWIPs [22,23]. Typical QEs obtained for p-QWIPs so far were in the order of a few percent [22,23,24]. It is not clear, however, whether the poor performance is due to the fact that investigated p-QWIPs were not optimized. Recent works on the optimization of p-type QWIPs were carried by Shen *et al.* [24], and the peak absorption QEs obtained were in the 4.5 to 6.6% range for 100 period QWs.

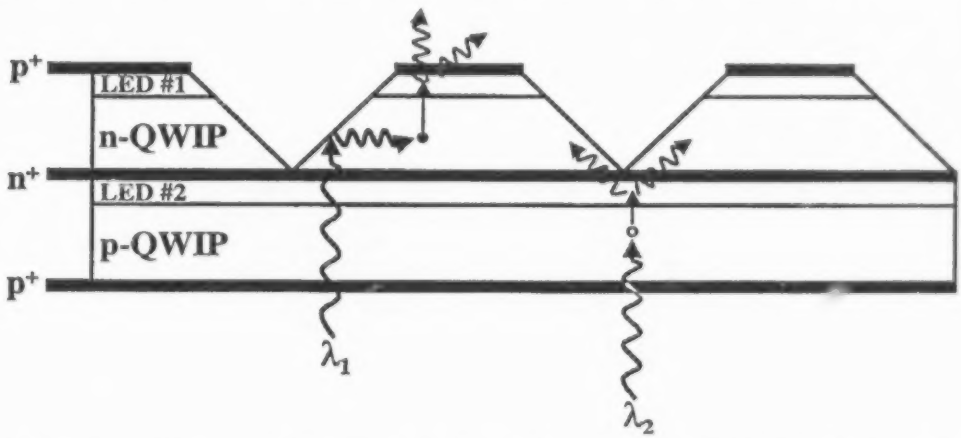

Figure 9 Schematic showing the layer structure of QWIP-LED architecture #3 with a V-groove coupler. A 2-D grating is preferred over the V-grooves for this layer structure.

The structure #4 allows the flexibility of using either a V-groove coupler or a 2-D grating without sacrificing either one of the LED layers. If the V-groove coupler were used, the etching needs to be only as deep as the n-QWIP layer thickness; see Figure 10.

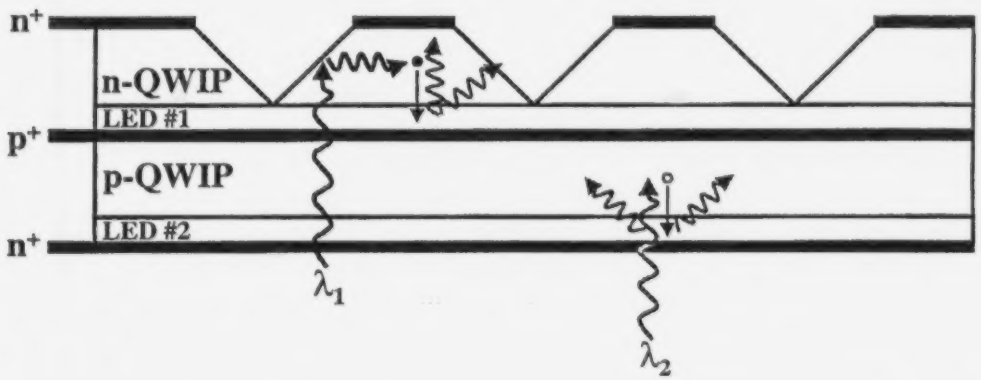

Figure 10 Schematic showing the layer structure of QWIP-LED architecture #4 with a V-groove coupler. A 2-D grating can also be used in place of V-grooves.

3. Simultaneous Multi-Spectral Imaging Schemes

3.1 Inherent Limitations of QWIP-LED Architecture

For Multi-lead QWIP-MUX devices, photocurrents are generated in separate QWIPs of different waveband responses by incoming IR lights of different wavelengths. Photocurrents from QWIPs can be independently collected by contacting leads and the simultaneous registration of multicolor images can be easily accomplished. Thus, in the QWIP-MUX scheme crosstalk between colors can be avoided with the Multi-lead approach. On the other hand, pixelless QWIP-LED devices present various obstacles to the designer in terms of achieving simultaneous multicolor registration. The reasons are as follow.

For Multi-lead QWIP-LED architecture, the photocarriers generated in separate QWIPs are converted to NIR lights by their respective LEDs. The difficulty lies in the fact that there is no simple way of differentiating the source of these NIR lights. Even if different bandgap LEDs were used (with LEDs emitting at different wavelengths), there will be significant crosstalk between the different wavelength NIR lights because LED lights of shorter wavelength will be absorbed by LEDs of longer wavelengths and reemitted at new wavelengths. Furthermore, even if the crosstalk can be minimized one still needs a CCD imaging chip that can differentiate NIR emissions of different

wavelengths. In other words, we need some method of differentiating or separating the NIR lights generated in the different QWIP-LED stacks. One possibility is to use spatial separation to differentiate between the NIR lights up-converted from LWIR (or VLWIR) lights of different wavelengths. This can be accomplished by an external checkerboard filter or a "built-in" checkerboard pixellation of the QWIP-LED large area device. These are discussed below.

3.2 External Checkerboard Filter

By placing an external checkerboard multicolor filter in front of the QWIP-LED large area device, one can spatially separate the incoming LWIR radiation into multiple images of different wavelengths. Figure 11 illustrates a bicolor QWIP-LED large area device with a bicolor checkerboard filter placed in front of the device. The filter can be a thin-film type deposited directly on the QWIP-LED or a separate filter placed at a focal plane of the integrated camera's optics. The images of different wavelengths are mapped onto different areas of the QWIP-LED device displaced slightly in space as determined by the checkeboard pattern. After the up-conversion of these LWIR images in the QWIP-LED layers, they are then mapped onto the CCD imaging array as shown in the figure. The images collected by the CCD array can then be separated by simple signal processing techniques as illustrated in Figure 12.

Incoming FIR Image
8-10 μm
12-14 μm
Two-color check filter
Filtered FIR Images
9 μm QWIP
14 μm QWIP
LED
CCD
CCD pixels image generated by 12-14 μm FIR
CCD pixels image generated by 8-10 μm FIR
Filter pixel size should be » pixel size of the CCD chip.
Two images are separated via signal processing.

Figure 11 **Implementation of a bicolor QWIP-LED focal plane with an external checkerboard bicolor filter.**

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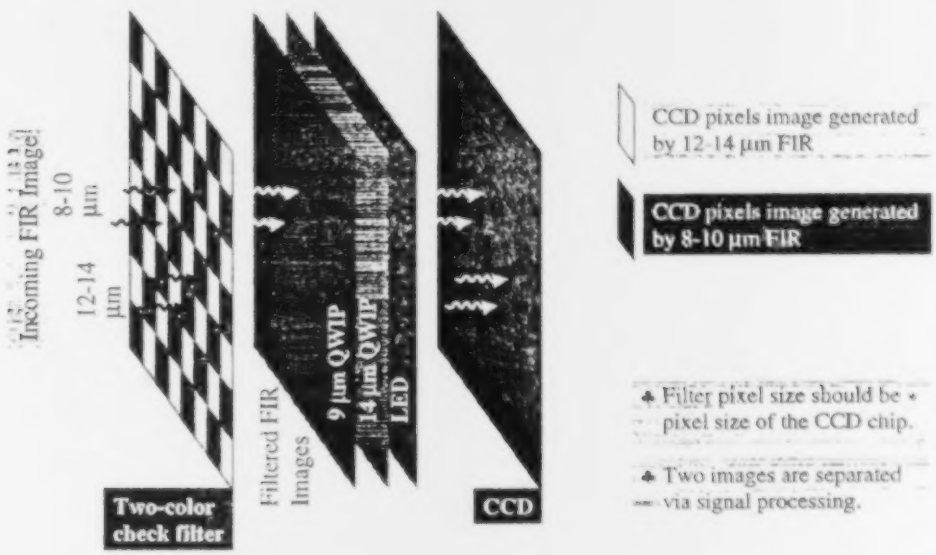
Incoming FIR Image
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Filtered FIR Images
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♣ Filter pixel size should be ♦ pixel size of the CCD chip.
♣ Two images are separated via signal processing.

Figure 11 **Implementation of a bicolor QWIP-LED focal plane with an external checkerboard bicolor filter.**

The multicolor images obtained are not exactly from the same LWIR source but rather are from spatially displaced neighboring sources. However, given that the checkerboard filter pixels are small compared to the area of the sensor, one can say that they are effectively from the same source.

This technique is simple both in design and fabrication and is applicable to both two-lead and Multi-lead QWIP-LED architectures. For the two-lead approach the crosstalk between colors can be avoided and the simultaneous multicolor registration is also achievable using this technique. The drawback is that the device's fill factor is significantly reduced. By dividing up the device into areas for different wavelength detection, we effectively reduce the active area available for the detection of a single color. So for a bicolor device we get a fill factor of only ~50 % for each color and for a tricolor device the single color fill factor becomes ~33.3 % and so on. Therefore the device fill factor decreases with the increasing number of colors.

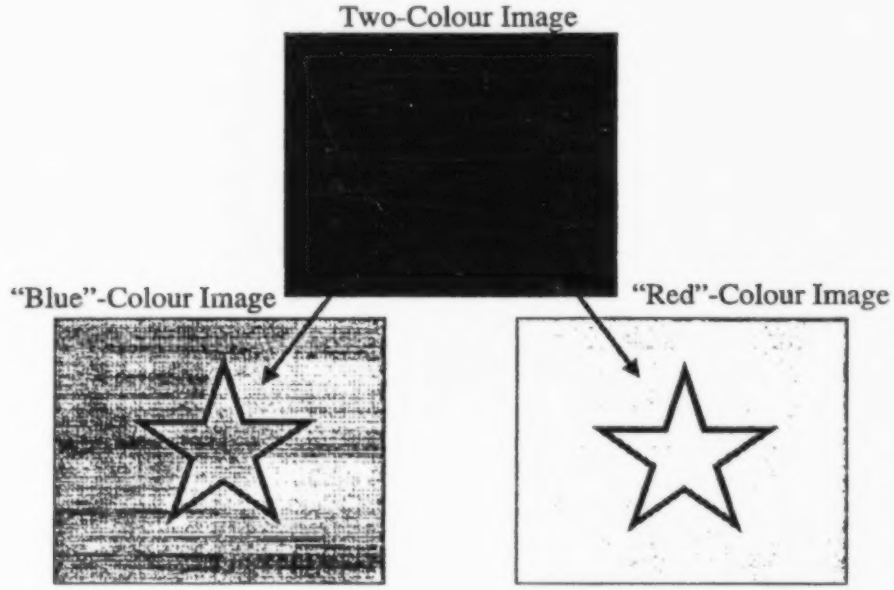

Figure 12 **The two color image can be separated into two single-color images by simple data processing techniques.**

Compared with a multicolor QWIP-MUX array, the checkerboard multicolor QWIP-LED approach will probably perform more poorly because of the reduced fill factor. Although a recent bicolor QWIP-MUX array implementation [25] utilizes an interlaced two-color pixel scheme which is similar to the checkerboard approach and, thus, suffers also the reduced fill factor problem. A more quantitative comparison can be made by looking at the two different architectures more closely. Figure 13 shows schematic

diagrams of a tricolor QWIP-MUX array and a tricolor checkerboard QWIP-LED device. For the QWIP-MUX array the single-color fill factor is reduced because parts of the top device active areas are removed to make room for the indium bumps to contact the intermediate contact layers; see Figure 13.1. Therefore in the case of p-type multicolor QWIP-MUX arrays (i.e., no grating requirement) the top QWIP layer would have a smaller fill factor than the lower QWIP layers because more active areas are removed in order to make contacts with the lower layer QWIPs. For n-type QWIP-MUX devices, all layers are equally affected by the number of contacts made because the grating resides on top of the array and would also have to be partly removed to make room for the indium bumps. For the tricolor checkerboard QWIP-LED device, on the other hand, the active area is divided into three regions of different colors as determined by the checkerboard filter pattern; see Figure 13.2. Thus, the single-color fill factor is equal to the *Total Active Area* divided by the *Number of Colors*. For this particular example the single-color fill factor is then 33.3 %.

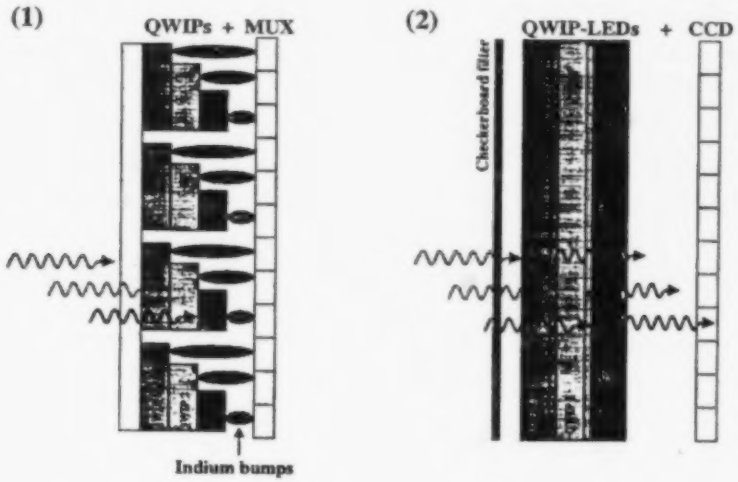

Figure 13 Comparison of a tricolor QWIP-LED device with a QWIP-MUX array: (1) Fill factor is dependent on indium bump contact areas; (2) Fill factor is inversely proportional to the number of colors.

An example of an actual bicolor QWIP-MUX array (showing only the QWIP part) is given in Figure 14 [19]. Two stacked one-color QWIPs separated by a doped GaAs layer which forms the intermediate contact are clad between a top and a bottom contact layers. To realize an array two contacts have to be defined on each pixel — the top and the intermediate one. The bottom contact is common to the whole array and is deposited around its periphery.

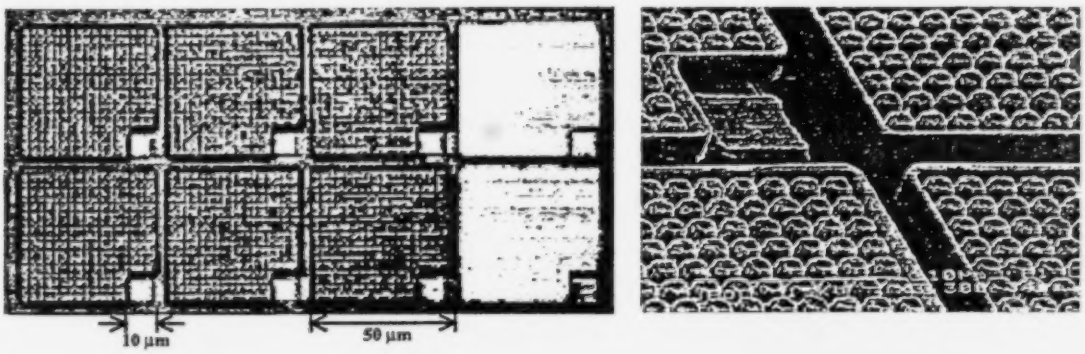

Figure 14 **SEM pictures of a bicolor QWIP focal plane array showing part of top QWIP layer removed to make room for contacting the intermediate contact layer [19].**

Minimizing the surface area of the intermediate contact will improve the performances (i.e., the fill factor) of the two QWIP stages. The indium bump electrode reduces the active area of the top detector and constitutes a zone without grating for the bottom stage. The current state-of-art bispectral QWIP arrays have typically a 50 µm pitch and a 10×10 μm^2 surface for the intermediate contact [19]; see Figure 14. The 10×10 μm^2 blind zone due to the intermediate contact will lead to a decrease in fill factor of about 5 % compared to a single color array of the same pitch. Thus, the total dead zone of this bicolor QWIP-MUX array, including the contacts and the groove areas between the pixels, is about 15 % (~ 85% fill factor). Similarly, for a tricolor QWIP-MUX array the estimated dead zone would be ~ 20 % (~ 80% fill factor) and so on. Comparing to the 50 % and 33.3 % fill factors of the bicolor and tricolor checkerboard QWIP-LED devices, the QWIP-MUX approach appears to be the undisputed winner. However, the fabrication of a large format three- or four-color QWIP-MUX array may present a serious technical obstacle that must be overcome.

3.3 Built-in Checkerboard Approach

Instead of using an external checkerboard filter, one can build into the device a checkerboard pattern which allows one area of the device to absorb IR light of one wavelength and the other area to absorb light of another wavelength. This can be done by removing either the top contact layer or the LED on certain part of the device in a checkerboard pattern. This is illustrated in Figure 15. For schemes using n-type QWIPs the checkerboard pattern can also be etched into the grating layer to allow certain portion of active area to absorb one wavelength and the other portion to absorb another. That is, two different gratings are interlaced in a checkeboard pattern.

This built-in checkerboard approach, however, works only for bicolor devices. For devices with more than two colors the fabrication challenge may become insurmountable. Even for bicolor devices the scheme requires backside patterning, which may already be a very difficult task for the microfabrication. Also the scheme suffers the same problem as that of the external checkerboard scheme — a reduced fill factor.

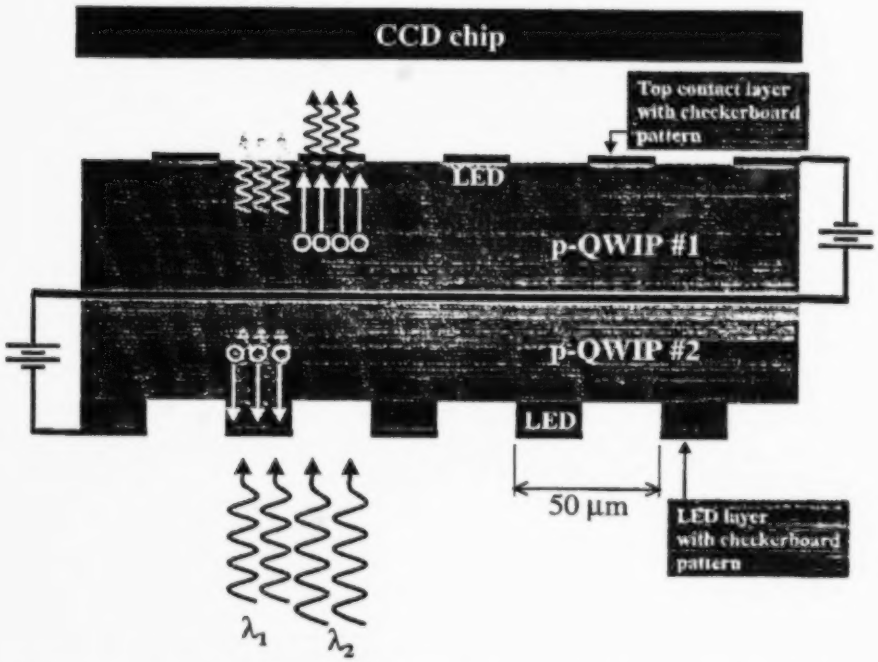

Figure 15 **Shown on the top QWIP-LED stack is the top contact layer with checkerboard pattern so that only areas with the contact layer will have the bias voltage to induce photocurrent. The bottom QWIP-LED stack has similar built-in checkerboard implementation except the pattern is built into the LED layer. Similarly for n-type QWIPs the same can be patterned into the grating layer.**

3.4 A Bicolor QWIP-LED device with near 100% Fill Factor

In order to remedy the fill factor problem with the above multicolor QWIP-LED schemes, we propose the following modifications to the built-in checkerboard approach. The scheme uses two p-type QWIPs grown next to each other with a contact layer separating them as shown in Figure 16. The two distinctive features about this design are: (1) an additional thin conductive layer is clad between the QWIP and the LED and (2) both the LED and the conductive layer are pixellated. The conductive layer allows a constant voltage difference to be maintained across the QWIP layer and, thus, keeps the whole layer active. The layer also permits photocarriers to flow freely in it once they

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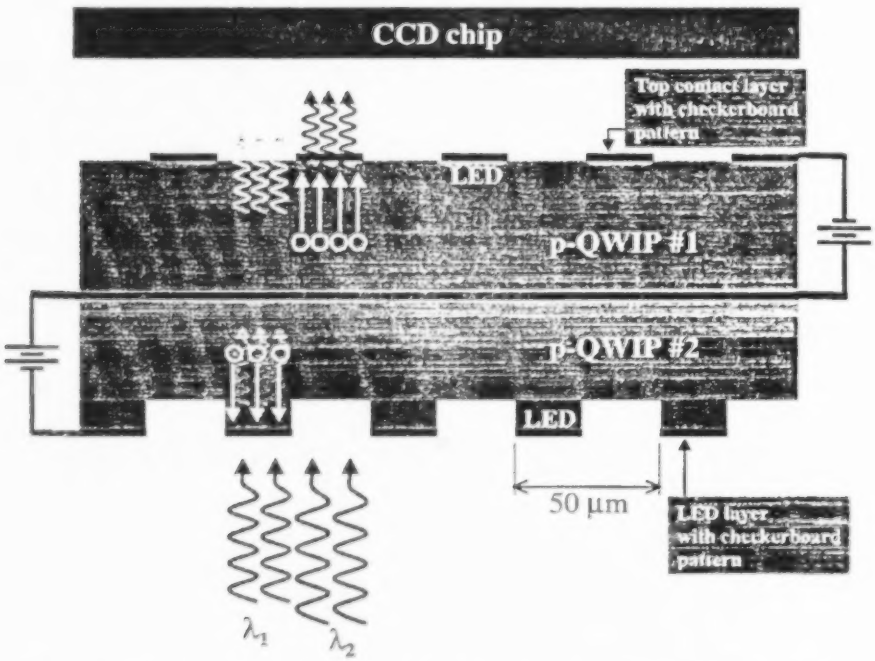

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reach the QWIP-LED interface; see Figure 16. The pixellation of the conductive layer is needed to confine the photocarriers to within a pixel area ($25\times50\ \mu m^2$) in order to avoid image smearing. The pixellation of the LED layer ensures that the NIR lights from the top and the bottom LEDs are spatially (i.e., laterally) separated for the simultaneous two-color registration at the CCD stage; see Figure 16. Since the LEDs are operating in the small current regime, removing part of LED active regions is not expected to degrade their performances. However, the passivation of LED edges would be required in order to avoid nonradiative recombination losses.

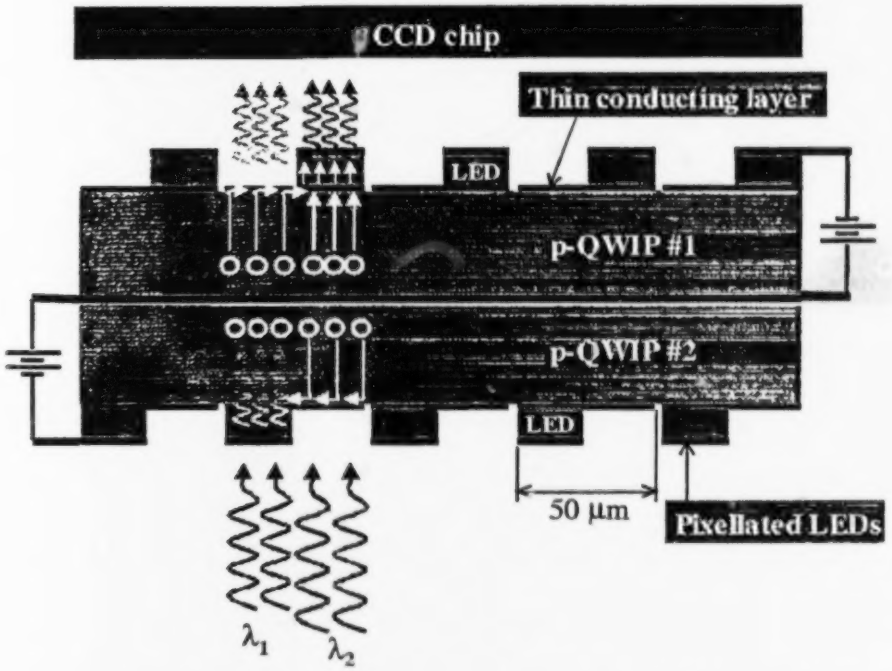

Figure 16 **Implementation of a bicolor QWIP-LED focal plane with built-in checkerboad for spatial waveband separation. Near 100% fill factor can be accomplished using this archetecture.**

The proposed scheme requires that we use p-type QWIPs. Using n-type QWIPs could lead to insurmountable fabrication difficulties as 2-D gratings or V-groove couplers are also required and need to be incorporated into the already-complicated design. This QWIP-LED scheme is also very much restricted to bicolor devices as discussed above. The 2-D array layout of the device is shown in Figure 17. As can be seen, the LED pixels have a square shape while the underneath conductive layer is etched into a rectangle. It should be noted that the QWIP layers remain pixelless and there is not reduction in the QWIP fill factors.

In order to avoid having to contact every pixel in the array, one needs to connect all the LED pixels together at the top contact layers by metal wires as represented by the yellow dots in Figure 17. This again may require a real microfabrication feat. However, in principle the scheme is realizable, and promises to offer a signification improvement in detector performance.

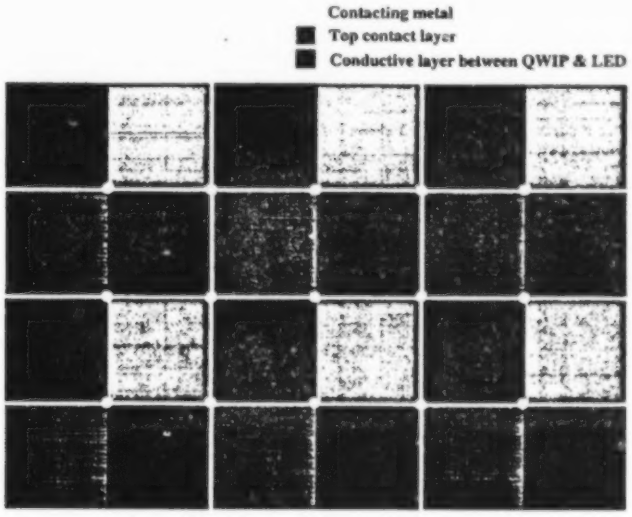

Figure 17 **A bicolor QWIP-LED focal plane array with checkerboard pattern etched into the top contact, the LED, and the intermediate thin conductive layers. The rectangular QWIP-LED pixels are connected to each other at the top contact layer by metal deposits.**

4. Other Simultaneous Imaging Schemes

There are other simultaneous multicolor implementation techniques that deserve mentioning briefly here. They are the conventional beam splitter method and the Brewster's angle beam splitter approach. These are simple techniques that can be implemented without very involved optic alignment requirements.

4.1 Waveband beam splitter approach

A simple waveband beam splitter is placed exactly at 45° with respect to two QWIP-LED devices; see Figure 18. The two QWIP-LEDs are in turn at 90° with respect to each other. The beam splitter allows, for instance, the 8-10 μm image to pass through it and focuses the image onto the QWIP-LED #1 and diverts the 12-14 μm image at 90° from the incoming direction and focuses it onto the QWIP-LED #2. This symmetric arrangement ensures that the two IR images can be simultaneously mapped onto the two

QWIP-LED devices placed at the focal plane of the preceding optics. Using this method one can simultaneously register either two colors, four colors, or six colors if two single-color, bicolor, or tricolor QWIP arrays are used, respectively. This is a simple way of doubling the detector's multicolor capability without having to redesign the device architecture completely. Moreover, one would expect the materials problem to become unmanageable as one attempts to grow more than three stacks of QWIP-LED layers on top of each other since the defect density increases with the device thickness.

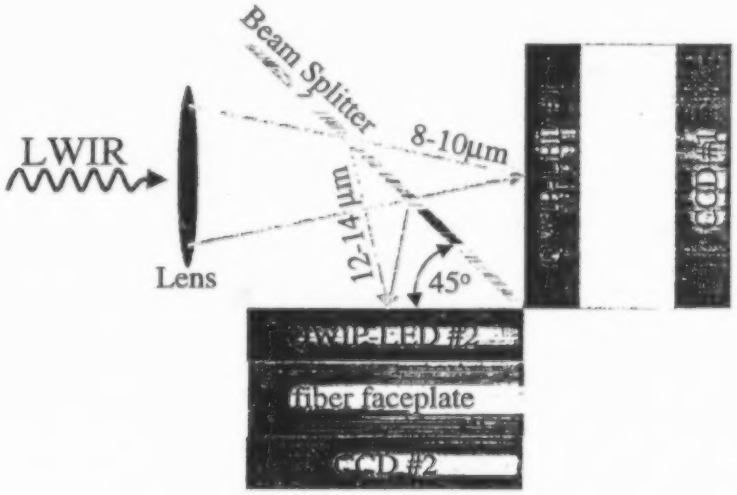

Figure 18 **The incoming IR images are separated according to their wavelengths by a waveband beam splitter placed exactly at 45° with respect to the two QWIP-LED focal planes.**

4.2 Brewster's angle beam splitter approach

The Brewster's angle beam splitter approach is similar to that of the waveband beam splitter, but instead of separating the incoming IR lights according to their wavelengths the IR image is split into two separate S- and P-polarized images as depicted in Figure 19. The two separated images retain their full spectrum but keeping only a component of their original electric field vectors.

This scheme is particularly attractive when one opts the lamellar V-grooves as the optical coupler for n-type QWIPs. Since the V-groove coupler can only couple one component of the electric field vector, one does not lose anything for retaining only one polarization component for each split IR image as long as the V-grooves are oriented perpendicularly to the electric field vector S- and P-components; see Figure 19. The

optical alignment for this approach, however, may be more demanding than that of the waveband beam splitter.

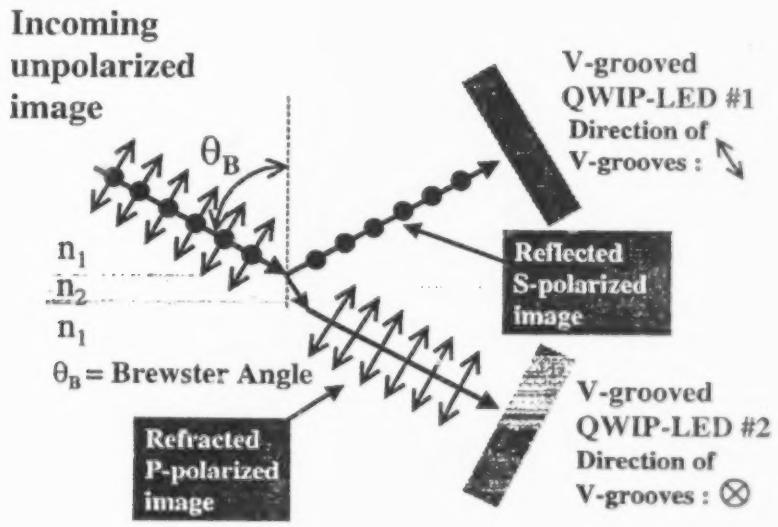

Figure 19 **The incoming IR image are split into two separate S- and P-polarized images by a dielectric surface placed at an angle equal to $90-\theta_B$ with respect to the incoming IR beam. These images can then detected by two QWIP-LED devices at the paths of the two outgoing beams.**

4.3 Comparision with "multi-stack" approach

As we already mentioned before, the defect density increases with the number of color stacks that we add on to the device. Also, the fabrication complexity may become unmanageable if more than two layers of QWIP-LED stacks are to be etched into checkerboard patterns. Therefore, even though the beam splitter method may not be as compact or elegant as the multi-stack approach, the technique should be seriously considered as a possible design option when more than two or three colors are required. The multi-stack approach may appear to be a simple and elegant way to achieving multicolor capability, but after considering the growth difficulty and fabrication complexity it may not be as simple as it first appeared. The beam splitter method could in fact offer a far simpler way of accomplishing the same thing without having to face the aforementioned obstacles.

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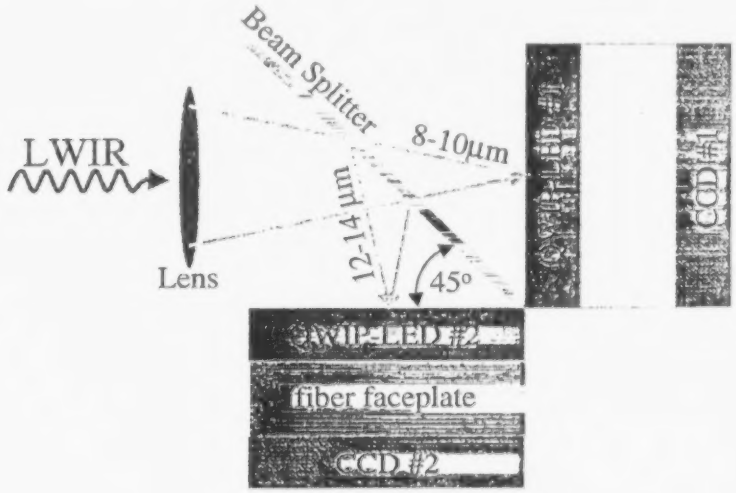

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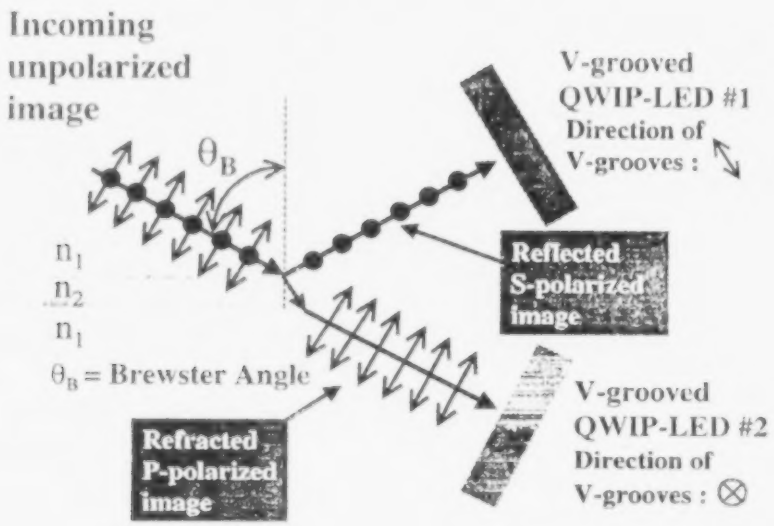

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5. Conclusions

As the infrared technology continues to advance, there is a growing demand for multispectral (or multicolor) detectors with better and faster target discrimination and identification. This study identified the current QWIP multi-spectral implementation methods and adapted them to the QWIP-LED architecture. The QWIP-LED approach has its unique design constraints associated with its optoelectronic imaging scheme. Some of its inherent limitations to achieving simultaneous multispectral registration were also discussed. Several multicolor QWIP-LED implementations were described, including two-lead pixelless QWIP-LED devices with sequential multicolor registration and Multi-lead bicolor QWIP-LED focal plane array with near 100% fill factor.

Future directions for research should include the study of p-type QWIPs with an emphasis on optimization techniques such as implementation of microcavity for LWIR absorption enhancement. Also, backside patterning techniques should be explored in order to facilitate the implementation of bicolor QWIP-LED devices with a near unity fill factor. Furthermore, one needs to look into V-groove passivation methods to allow the utilization of V-groove couplers in some of the QWIP-LED geometry examined.

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The recent advances in infrared sensing technology has made it possible to use infrared sensors to support environmental observations, surveillance, threat detection, tracking, and target identification. For space-based ballistic missile defence (BMD) related applications, the most important detector requirements are: high sensitivity, high uniformity, large format, and multicolor capabilities. Quantum well infrared photodetectors (QWIPs) are a relatively new candidate technology for BMD applications. The current Canadian QWIP technology is based on integration of the QWIP with a light emitting diode (QWIP-LED). As the infrared technology continues to advance, there is a growing demand for multispectral (or multicolor) detectors with better target discrimination and identification. The objects of this study are first to identify the current QWIP multi-spectral implementation techniques and then to adapt them to the new QWIP-LED imaging scheme. The scheme has its unique design constraints associated with the QWIP-LED architecture. Some inherent limitations of the QWIP-LED scheme to achieving simultaneous multispectral registration are also discussed. Several multicolor QWIP-LED implementations are described, including two-leads pixelless QWIP-LED devices with sequential multicolor registration and multi-leads bicolor QWIP-LED focal plane array with near 100% fill factor.

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